Environmental Research in California and Beyond

From earthquake prediction to groundwater quality, environmental research projects focused on California have implications far beyond the state's borders.

EARTH, air, fire, water . . . Aristotle's four basic elements of matter come under a great deal of scrutiny in many of the environmental and geologic projects at Lawrence Livermore. Some of this research springs from issues of particular interest to California, such as groundwater quality or earthquake prediction.

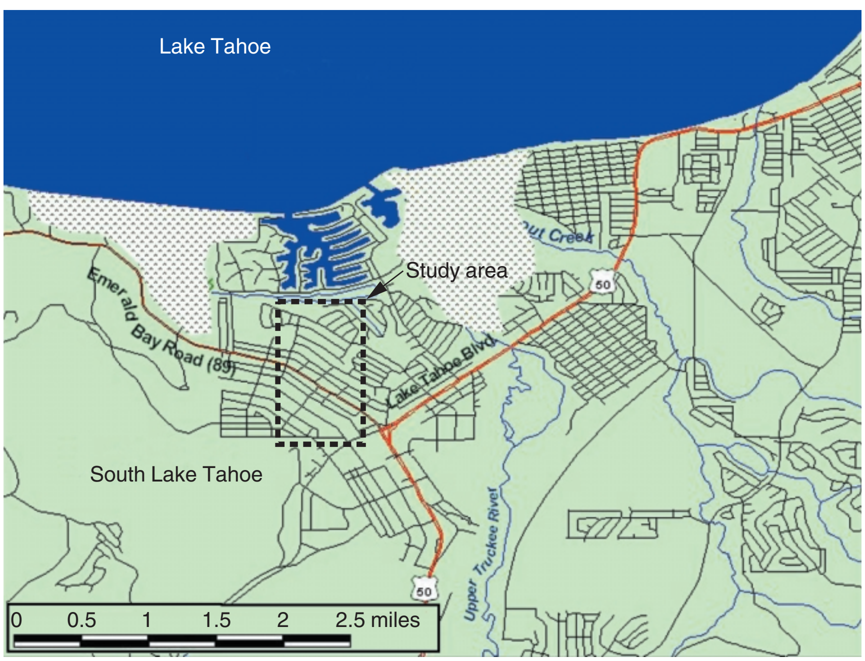
The Energy and Environment Directorate, with the help of other groups across the Laboratory, is a natural for contributing in this arena. For example, Robin Newmark, a geophysicist in Energy and Environment, helped develop thermal remediation technologies such as dynamic underground stripping and hydrous pyrolysis/oxidation that are being used to clean up contaminated groundwater sites at both government and privately owned facilities across the country. These technologies have been used at Lawrence Livermore and in Visalia, California, and are under consideration by the U.S. and California Environmental Protection agencies for use at other sites. She notes, "We have a number of small and mid-sized projects with a California perspective, and others that have great potential for more interplay with the state community."

Dave Layton, division leader for Health and Ecological Assessment, agrees. "I'd like to see our research portfolio push further into California."

In one current project funded by the California State Water Quality Control Board, researchers from Energy and Environment, along with colleagues from the Chemistry and Materials Science Directorate and the Environmental Protection Department's Environmental Restoration Division, are using isotopic tracers to examine the vulnerability of groundwater to volatile organic compounds and other chemicals. Meanwhile, out on dry land, researchers from the Biology and Biotechnology Research Program and the Energy and Environment directorates are developing a DNA-based measurement technology that will help them study the environmental factors that allow the Valley Fever fungus to thrive in California's Central Valley. Another California-centric example is a recent workshop hosted by the Laboratory and sponsored by the Department of Energy's Office of Fuels Development and the Western States Petroleum Association. The workshop focused on the increased use of ethanol and alkylates in automotive fuels in California after a phaseout of the potentially toxic MTBE fuel additive.

Unique Laboratory capabilities are also being used to help California with environmental issues. The Atmospheric Release and Advisory Capability (ARAC) came to the aid of the California Environmental Protection Agency three years ago, using computer simulations to monitor smoke billowing from a 30-acre tire fire near Tracy, California (see *S&TR*, June 1999, pp. 4–11). The Environmental Restoration Division developed GeoTracker, a public Web site (http://geotracker2.arsenaultlegg.com/), which helps California regulators and the public evaluate the safety of drinking water by identifying leaking underground fuel tanks and their proximity to municipal water wells (see *S&TR*, July/August 2000, p. 2). A digital mapping or geographic information systems capability that allows users to sift through layers of geographic data (such as population densities, elevation data, and earthquake faults) will support the California Energy Commission in siting future power plants to alleviate the current California energy crisis.

Three projects with a subterranean focus—two on groundwater and one on earthquakes—provide examples of what the Laboratory is doing to address environmental issues of importance to California and beyond. In a fourth, large-scale effort—a joint vision of Lawrence Livermore and the University of California at Merced—environmental research related to the California Central Valley and the Sierra Nevada would be integrated into a supercomputer- and sensor-driven "Virtual Valley," with resources available to planners and public alike.



Map of a portion of South Lake Tahoe showing the area being modeled to determine how MTBE moves in groundwater.

Assessing MTBE Mitigation

Since 1992, many U.S. oil refineries have been adding MTBE (methyl tertiary-butyl ether) to gasoline to reduce air pollution and fulfill a requirement of the federal Clean Air Act. However, MTBE has turned out to have certain drawbacks. Once it gets into the ground—through spills and leaks—it can infiltrate groundwater supplies, giving drinking water an unpleasant taste and odor. "The taste is noticeable even at very small quantities—down to 5 micrograms of MTBE per liter of water," notes Laboratory hydrogeologist Steven Carle. Some evidence also suggests that MTBE may be a human carcinogen.

These are no small issues. Groundwater is a significant source of drinking water worldwide. In the United States alone, 60 percent of the water used is groundwater. In California, at least 10 public drinking water wells have been closed because of the intrusion of MTBE.

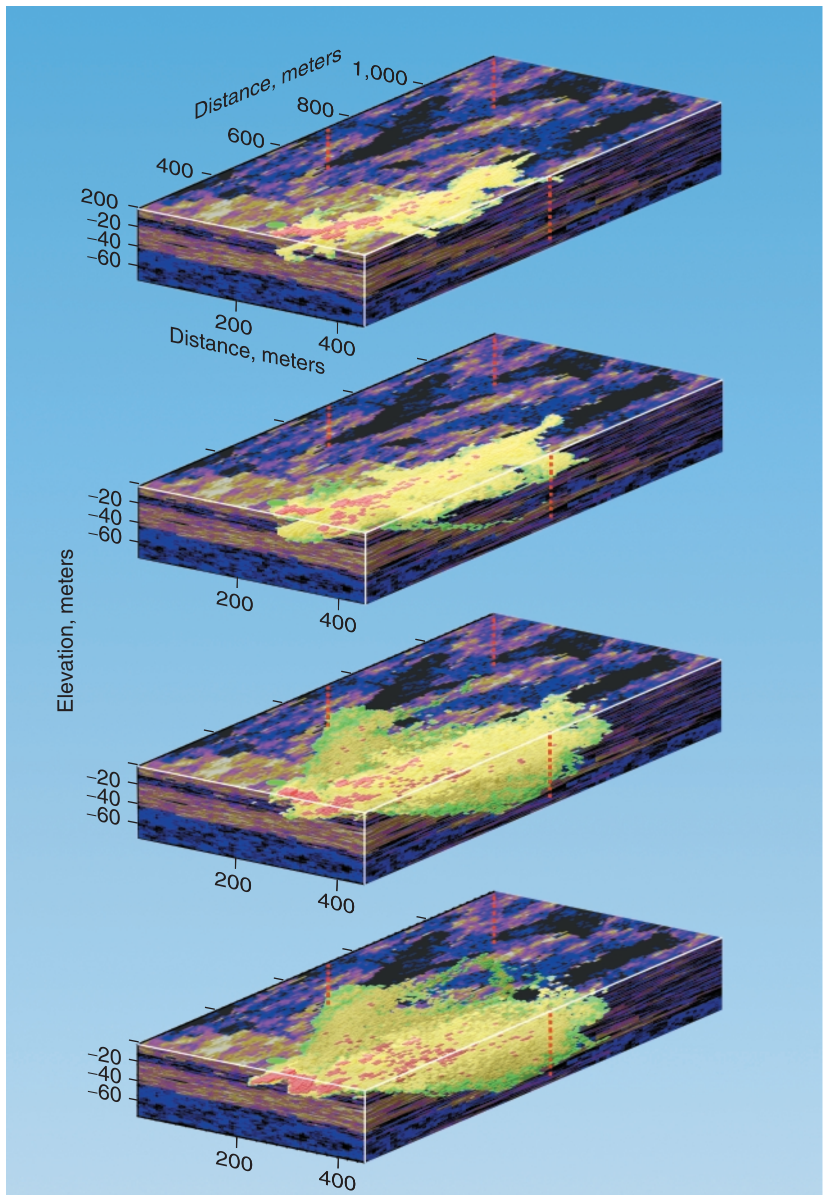
With this as background, Laboratory researchers Carle, Reed Maxwell, and Dave Layton developed three-dimensional computer simulations of how MTBE moves underground. As it turns out, MTBE behaves differently in groundwater from other petroleum products such as benzene: it is highly soluble in water, does not easily adsorb to soil, and does not degrade readily on its own. The team chose South Lake Tahoe as the location to model. "MTBE could be a crucial issue for this area," Carle says. "The South Lake Tahoe area receives lots of recharge in the spring from melting snow. The snow melts into the ground, causing pressure to build up that flushes the groundwater and anything in it quickly through the subsurface system."

Carle and the team set about creating a realistic geologic model of the area using information supplied by the South Lake Tahoe Public Utilities District. The subsurface is complex, notes Carle, with the aquifer systems spanning multiple geologic formations. Using TSIM, a geostatistical simulation code developed by Carle, the researchers built a below-surface model of the geology of the area as well as of the permeability of the various layers and subterranean features.

"We had to use a certain amount of statistical interpolation," says Carle. "Even though we used information gained from core samples and geologic studies of the area, we don't know, inch by inch, exactly what's down there." The model of the area—a chunk of real estate 600 meters by 1,200 meters—was built up of 7.2 million wafer-thin geologic "cells," 5 by 10 by 0.2 meters. "We ended up with a problem consisting of millions of cells, with materials that had permeabilities differing by seven orders of magnitude," he says. It was the first time that both the geology and permeability of this area had been simulated in such detail.

The team then placed four municipal wells in the model at their proper locations and set up a realistic model of a leaking underground tank: a constantly replenished pool of MTBE (1.5 kilograms per day) just under the surface, dissolving into groundwater over 300 days. Knowing the pumping rates of the wells, the team was able to use ParFlow (a parallel finite-difference numerical flow modeling code developed at the Laboratory) to calculate a high-resolution flow field. The flow field indicates the direction that water and other liquids flow below the surface, rather like a topographic map allows determination of the direction of flow on the surface.

Finally, the simulations were fed into SLIM-Fast, a numerical particle-tracking code, to trace the fate of MTBE. "With this code, tracking MTBE particles in the groundwater is like tracking a bunch of ping-pong balls in a river," explains Carle. SLIM-Fast also permits "splitting" of the MTBE particles, allowing researchers to track increasingly dilute concentrations of MTBE. "This was a first," notes Carle. "Most other codes cannot trace the ultimate fate of MTBE because they can't accurately reach the low concentrations that evolve over time." Using the three codes, the researchers tracked the MTBE over a 30-year period to its final dilutions in the wells.



This four-part simulation shows an extensive MTBE plume increasing the contamination of nearby wells over time.

The team also generated multiple scenarios using different geologic heterogeneities, all equally based on the information available, all equally plausible. “We generated a ‘cloud of predictions’ that helped us determine the uncertainties of our final results,” says Carle. The bottom line: According to the simulations, the most likely path of flow for MTBE leads directly to the water wells where it would show up in concentrations of tens of micrograms per liter.

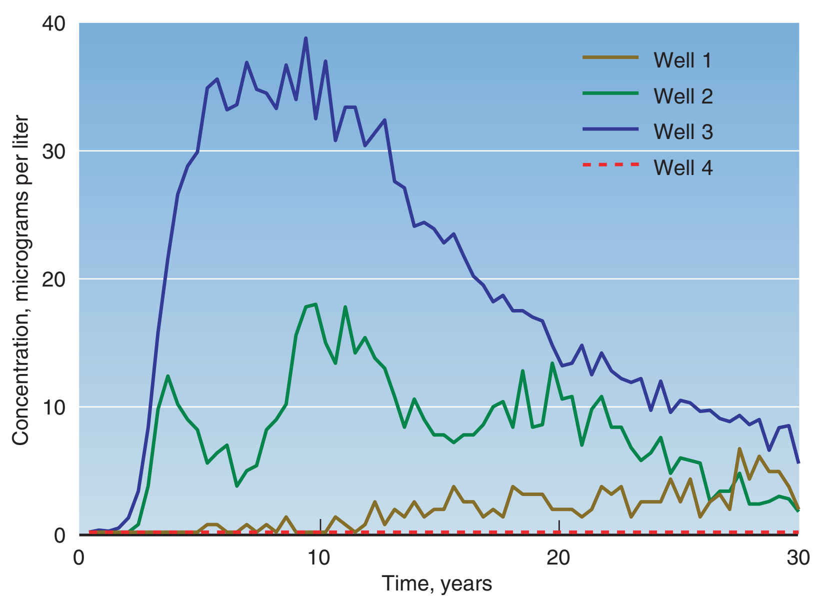
When the results were compared to an actual situation, the researchers found they were definitely in the ballpark. MTBE was found in seven South Lake Tahoe wells in concentrations of 0.5 to 68 micrograms per liter. One interesting result of the simulations indicates that the MTBE problem could persist for decades. “This was something we hadn’t expected,” says Carle. “We’d assumed—as did others in the field—that the MTBE moves along at the pace of groundwater. Instead, it appears that, through mechanisms we don’t fully understand yet, the MTBE lingers and is released over time. It could be that the chemical is slowing down in low-permeability zones. To explore this issue and others requires more realistic simulations that can produce better predictions.”

A (Water) Bug’s Life

Chemicals aren’t the only undesirables in the groundwater supplies. Microbes, viruses—“bugs” in popular parlance—also find a welcome environment in subterranean aquifers. Livermore’s Reed Maxwell worked with fellow researchers from the Laboratory, the U.S. Geological Survey, and Drexel University to better understand how these organisms are transported underground. Specifically, the team applied simulation and modeling techniques to see how the varied geology of riverbanks—sand, clay, cobbles, gravel, and so on—affect the movement of colloids (submicroscopic particles, such as viruses) dispersed in a different medium, such as water. Using a site in California’s Orange County for their simulations, the researchers examined how viruses could attach to different geologic media and compared the arrival time at the wells for both viruses and tracer chemicals often used to track groundwater movement. They also compared their results with results of simulations using models that assume a uniform, or homogeneous, type of material throughout—a riverbank composed of only sand, for instance.

“Water management districts such as Orange County are looking for better ways to manage and obtain clean sources of drinking water,” notes Maxwell. “In the process, researchers are examining technologies used over the past century in other countries and finding that these methods are actually quite effective in producing clean water.” For instance, a number of European countries obtain their water from the Rhine River by placing a well on the riverbank and pulling in river water through the subsurface of the bank. This riverbank filtration technique filters out much of the microbial activity in the water. “We’d like to better understand how this process works,” says Maxwell. “At what rate are these organisms filtered out? Do they stick to some particular medium, and if so, what medium and for how long? How does the transport of these colloids differ from that of tracer chemicals?”

These questions are of particular interest to Orange County. Nearly 80 percent of its water supply is composed of groundwater. The Orange County Water District is currently monitoring surface water and groundwater for viruses, but so far, it has detected none. Furthermore, Orange



Simulated MTBE breakthrough curves, showing concentration of MTBE in wells over time out to 30 years.

County is now considering using tertiary-treated wastewater (wastewater treated three times) to artificially recharge lakes, which will, over time, recharge groundwater aquifers. The Environmental Protection Agency has guidelines in place to ensure that such water is clean before it's used again.

Maxwell explains, "There are guidelines on such matters as the distances that wells must be from the water sources, and the 'residence time' that treated water must remain underground. These guidelines are expected to account for complicated natural processes that need to be better understood. Both wastewater recharge and riverbank filtration are potential pathways for microbes to contaminate drinking water sources, so understanding how various geologic media affect movement of these organisms is important."

To gain insight into how viruses move in groundwater and potentially prevent virus problems before they arise, Maxwell and his collaborators used a three-dimensional computer model developed by Laboratory hydrologist Andrew Tompson to simulate the movement of groundwater in an area used in a water reclamation operation managed by the Orange County Water District.

Three wells were studied. Two (PL--5 and PL-10) derive much of their water directly from the Santa Ana River, and one (P-4) receives recharge water from Anaheim Lake and Warner Basin, which in turn receive their water from the river. Water arriving at P-4 was about 1.3 years old, water at PL-5 was 0.5 year old, PL-10 water was 1.2 years old. Although PL-3 is closer to the water source than PL-5, the same water actually takes longer to travel the shorter distance because of the permeability and complexity of the subsurface. This anomaly, Maxwell notes, would not have appeared if the geologic model had been homogeneous.

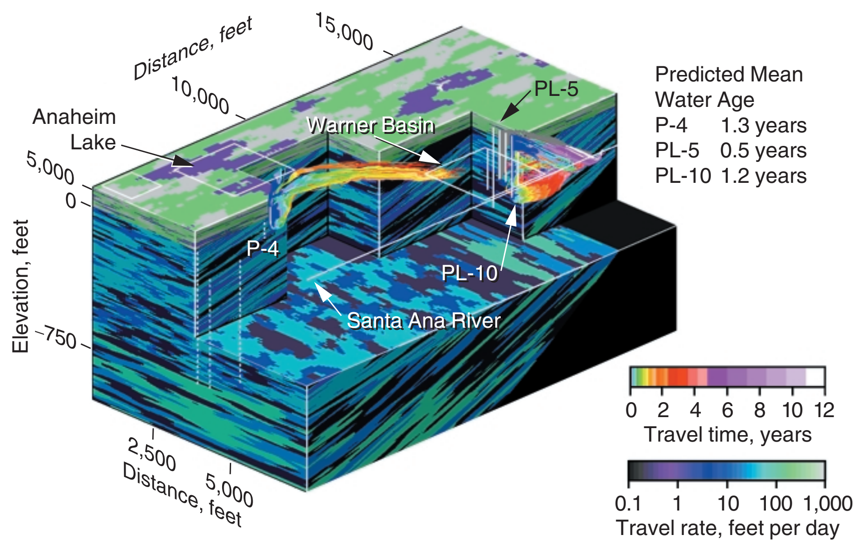
The team took this three-dimensional model and numerically built in the ways in which submicrometer-size organisms attach and detach from the materials found beneath the surface. From there, the team deconvolved the problem. That is, they took the complicated three-dimensional flow field that simulates the motion of groundwater, its tracers, and its hitchhiking organisms and broke it down into a number of one-dimensional transport problems. The problems were solved using Livermore's massively parallel computing systems. The results were then recombined to find out what arrived first at the wells.

A tracer chemical was first to break through into the simulated wells and displayed the highest concentrations at the wells over time. The viruses broke through last and showed the lowest concentrations. "What that told us is that the well is most vulnerable to a tracer . . . not to microbes." says Maxwell. "Tracer chemicals, in other words, are poor predictors of viral arrival times in wells according to this particular model. These results show the importance of using a model that accurately reproduces the geology of the given area."

There are, he adds, many more questions regarding microbial transport in groundwater. "It's pretty clear that different filtration processes dominate for different types of soil. Less permeable sediments—tightly packed sand, for instance—are good at filtering out microbes. We still have a ways to go in understanding the physics of viral transport in the subsurface."

In Search of Ancient Earthquakes

What could be more California than earthquakes? The San Francisco Bay Area has the highest density of active faults and the highest rate of seismic moment release per square kilometer of any urban area in the U.S. In 1998, in the hope of providing a framework for more precise forecasts of future large and damaging quakes, the Center for Accelerator Mass Spectrometry (CAMS) at Livermore joined a multi-institutional effort, led by the U.S. Geological Survey, in a region-



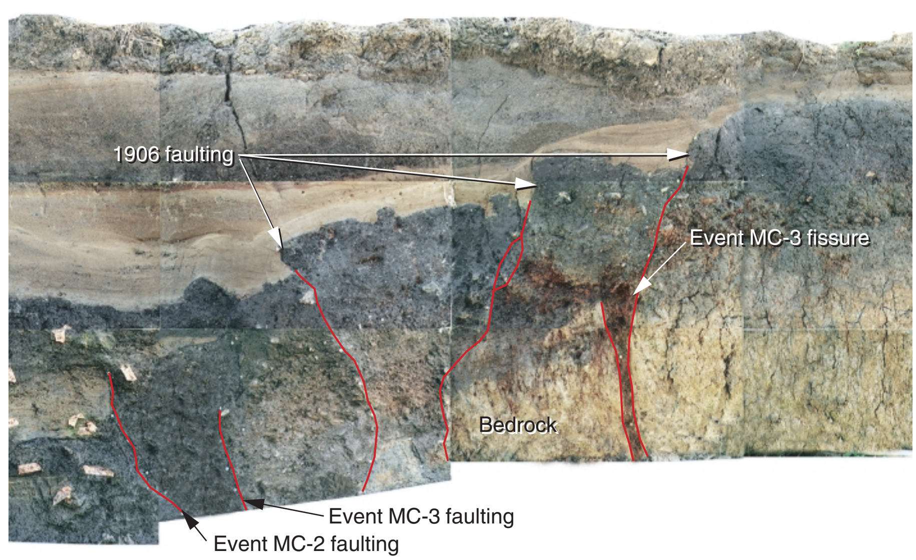
Computer simulation of the subsurface geology, the streamlines tracing travel paths of groundwater, and the predicted mean age of the water as it travels from recharge sources to wells P-4, PL-5, and PL-10.

wide cooperative project called the Bay Area Paleoseismic Experiment, or BAPEX.

BAPEX's goal is to develop a 2,000-year chronology of large earthquakes in the Bay Area and look for patterns in the timing, locations, and magnitudes of prehistoric shakers. Unlike other paleoearthquake projects, which usually limit their focus to the history of a single fault, BAPEX targets essentially an entire plate boundary. This region—the 45-kilometer-wide area between the San Gregorio and Greenville fault zones from west to east—represents most of the plate boundary between the Pacific and North American plates. As part of that effort, geologists such as Livermore's Gordon Seitz are focusing on the area's seven major fault systems—the San Andreas, San Gregorio, Hayward, Rodgers Creek, Calaveras, Concord–Green Valley, and Greenville.

Seitz explains, "When we find a promising site, we excavate down as far as 9 meters and examine the geologic layers or strata. Although most earthquakes are triggered 10 to 15 kilometers below the surface, large earthquakes cause ground rupture,

The San Francisco Bay Area is located within the Pacific–North American plate boundary. The focus of the Bay Area Paleoseismic Experiment has been to develop past earthquake chronologies on the seven major faults in the area: the San Gregorio, San Andreas, Hayward, Calaveras, Rodgers Creek, Concord–Green Valley, and Greenville faults.

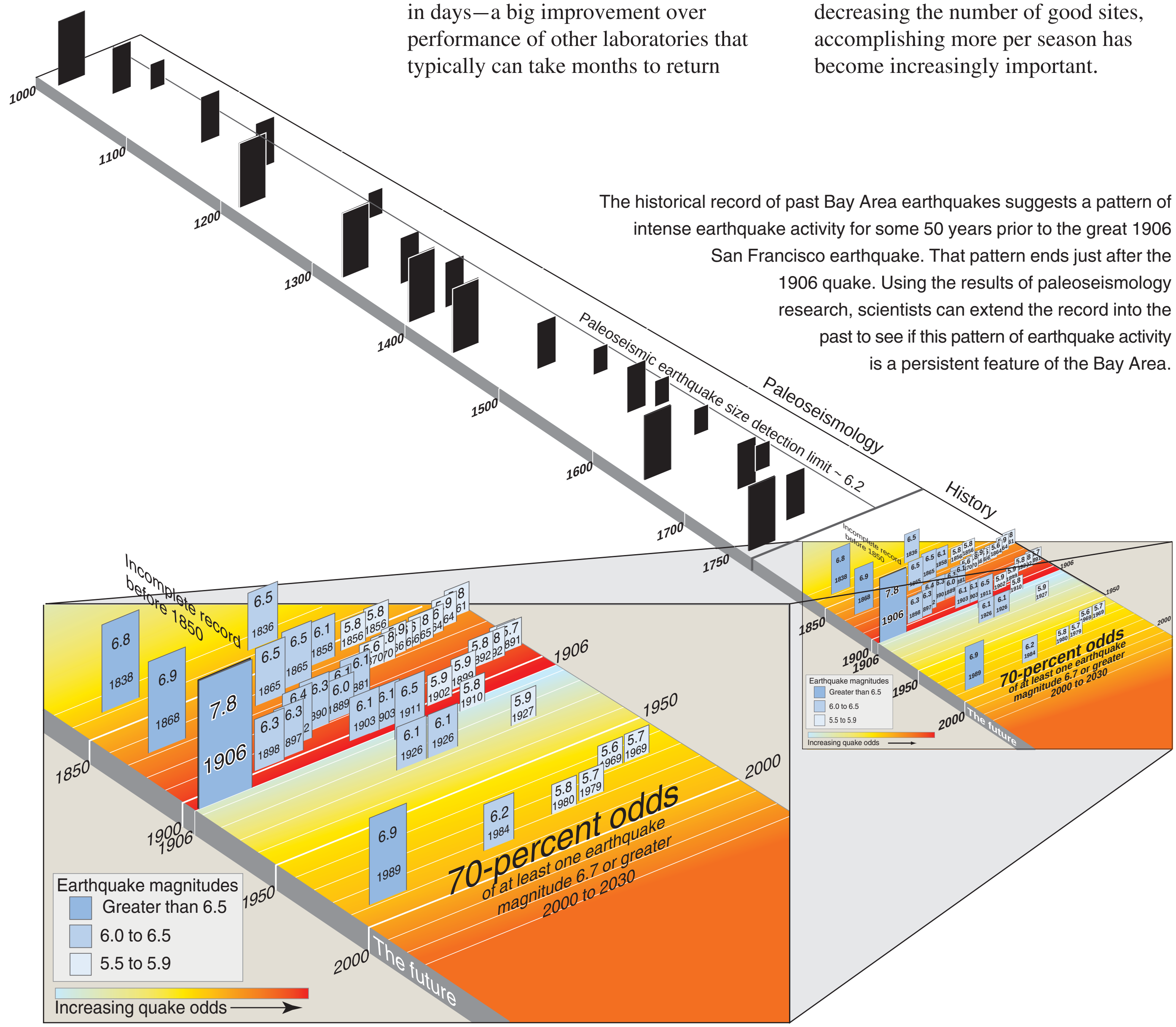


This photomosaic trench log, a vertical cross section of the San Andreas Fault at Mill Canyon near Watsonville, California, shows evidence of three past earthquakes—the San Francisco earthquake of 1906 and two previous events labeled MC-2 and MC-3. Each of these earthquakes produced characteristic downward-tapered infilled fissures. (This study was led by Tom Fumal at the U.S. Geological Survey.)

which is recorded in these near-surface layers.” In cross-cuts through the strata of a fault zone tens of meters in width, the researchers look for evidence of former ground-rupturing deformation such as fault scarps at the surface or buried beneath it, fissure fills, upward-terminating faults, folds, and sand volcanoes. When geologists find such layers, they look for organic material within the sediments that can be carbon dated at CAMS.

Not much material is required for dating. About one-thousandth of a gram—an amount equal to a couple grains of dirt—will do. The age of the material is determined by the amount of carbon-14, or radioactive carbon, in the sample. The Livermore accelerator is extremely sensitive, able to find one carbon-14 isotope among a quadrillion other carbon atoms. (For more information on CAMS, see *S&TR*, July/August 2000, pp. 12–19.)

The CAMS team can produce results in days—a big improvement over performance of other laboratories that typically can take months to return results to field geologists. “We call it real-time dating,” says Seitz. With CAMS as part of the process, geologists can quickly determine the age of key layers and move on to the next step in their fieldwork. “What used to take several seasons can now be accomplished in one season,” he adds. This quick turnaround is particularly important when the cross-cut or trench is located in an urban area and cannot be left open for more than a few days. And with urban development decreasing the number of good sites, accomplishing more per season has become increasingly important.



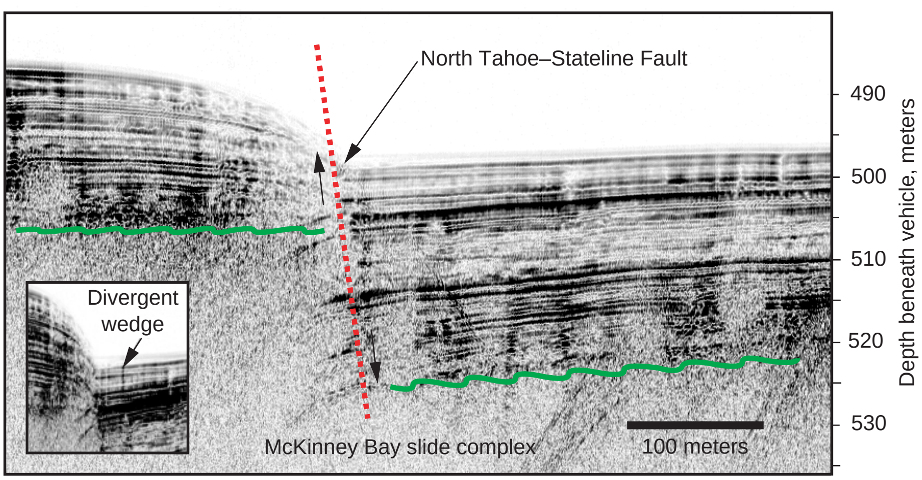
The historical record of past Bay Area earthquakes suggests a pattern of intense earthquake activity for some 50 years prior to the great 1906 San Francisco earthquake. That pattern ends just after the 1906 quake. Using the results of paleoseismology research, scientists can extend the record into the past to see if this pattern of earthquake activity is a persistent feature of the Bay Area.

BAPEX geologists have excavated more than 28 Bay Area paleoseismic sites and determined over 900 radiocarbon dates at CAMS. In the process, they've developed earthquake histories covering several thousand years for individual faults. To do a rigorous statistical analysis on the earthquake patterns, Seitz estimates that they need more event records covering longer periods of time. "Fourteen is the most I've seen recorded on any one site," he notes.

When a comparison of timing and magnitudes is made between "historic" northern California earthquakes (1850 to present) and "prehistoric" quakes, a pattern emerges: Leading up to the 1906 quake, the magnitude and frequency of earthquakes increased; after 1906, activity shut off for more than 50 years. Is the Bay Area at the start of another cycle, with the1989 Loma Prieta quake being the first major quake?

"We can't say for certain," says Seitz. "Historically, the Bay Area has not experienced one complete earthquake cycle. But by the best estimate of the experts, there's a 70-percent chance in the next 30 years that the Bay Area will see a quake of magnitude 6.7 or greater quite possibly centered in a heavily populated urban area. BAPEX should cast some additional light on these forecasts by providing a more complete picture of earthquake patterns over time and space."

Seitz, along with Graham Kent of the Scripps Institution of Oceanography at the University of California at San Diego, is extending this research by taking a close look at paleoearthquakes under water. "Previously, the research of paleoearthquakes has focused on dry land," he explains, "because underwater trenching is not yet possible. But in light of several major technological advances—high-resolution seismic imaging, accelerator mass spectrometry's ability to provide carbon-14 analysis of small samples, and detailed bathymetry mapping—we wondered how fault investigations could be done offshore."



A seismic profile at unprecedented submeter resolution across the North Tahoe–Stateline Fault at a water depth of about 500 meters. The unique high resolution of this profile is achieved by sweeping the source through a range of frequencies (500 hertz to 15 kilohertz), a technique developed largely by Neal Driscoll, now at the Scripps Institution in San Diego. The thickening of sediments near the fault on the downthrown right side block is characteristic of sedimentation after an earthquake.

Seitz and Kent turned to a new high-resolution seismic technique called CHIRP to help with underwater paleoseismic studies. Like a sonar system, CHIRP bounces sound waves off submerged structures. However, unlike sonar, the CHIRP system can image sediment layers beneath the lakebed at unprecedented resolutions. "With CHIRP, we can image layers as thin as 20 centimeters," he says. Using Lake Tahoe as a test bed, the team created seismic profiles at the bottom of the lake with imaging depths of as much as 50 meters.

The use of CHIRP technology in seismic hazard assessment is new, notes Seitz. Skills learned at Lake Tahoe will not only help solve many of the outstanding local questions, but in the future, they could also be used to understand a subset of neotectonic problems that are hidden underwater.

Says Seitz, "Our approach of 'acoustic trenching' combined with carbon dating of strategically located sediment cores will, we hope, allow future studies of many active fault systems that have been largely ignored, mostly because of water coverage. Being able to image the tectonically deformed sediments under water and having a way to determine their age are key."

Offshore faults along the California coastline and the parts of faults that extend offshore are examples of largely ignored fault systems that would benefit from underwater peleoearthquake research. International locales such as the Marmara Sea adjacent to quake-threatened Istanbul would also benefit from this technological advance. For Seitz, "Lake Tahoe is an ideal place to develop these techniques. The logistics are easier on this lake than at sea, and ship costs are 5 to 10 times less expensive."

Entering the Virtual Valley

Suppose one could take the Laboratory's environmental research capabilities and projects, join them to the research capabilities of a leading university, and focus them on a particular region. This is the premise of the Virtual Valley, a joint vision of Lawrence Livermore and the University of California at Merced, UC's newest campus, which is in the planning and development stage.

The Laboratory's activities to implement such a Virtual Valley concept would be pursued in partnership with those of UC Merced's Sierra Nevada Research Institute. The institute has been chartered to focus on the challenges surrounding the rapid development and transformation of California's Central Valley and Sierra Nevada region.

The task facing Virtual Valley designers and planners is to provide a comprehensive environmental simulation and observation system focused on regional issues. Issues the Virtual Valley might tackle include wildfire management and prediction, the effects of urban development, air quality and water resources management, earthquake prediction, and groundwater management and cleanup. The Virtual Valley will have the information, tools, and computational power needed to explore all these topics and more.

The Virtual Valley would tie together supercomputers, sensor networks, geographic information systems, field measurement sites, historical data sets, wireless communications simulation and modeling, advanced visualization systems, and Internet access. Its data sets and computing power would be available to students, educators, scientists, planners, residents, and the public-at-large.

Users would be able to combine diverse areas of environmental research together, look for commonalties, determine causes and effects, and work from a common platform. The effects of this research have the potential of reaching beyond California's borders. For example, other areas in the United States have groundwater management issues. Other countries must deal with the specter of devastating earthquakes. The Virtual Valley—and all of the research that could feed into it—provides us with a way to benefit the world, by focusing on the valleys and mountains out our backdoor.

—Ann Parker

Key Words: Bay Areas Paleoseismic Experiment (BAPEX), Center for Mass Accelerator Spectrometry (CAMS), CHIRP, groundwater management, hydrogeology, MTBE, Orange County, paleoearthquakes, ParFlow, San Andreas Fault, SLIM-Fast, South Lake Tahoe, TSIM, University of California at Merced, Virtual Valley.

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About the Scientists

REED MAXWELL (left) holds a B.S. from the University of Miami (1992) and an M.S. from the University of California at Los Angeles (1994) in mechanical engineering, and a Ph.D. from the University of California at Berkeley (1998) in civil and environmental engineering. He joined the Laboratory as a postdoctoral fellow in 1998 and became a physicist in the Geosciences and Environmental Technologies Division in 2000. He specializes in the study of radionuclide transport at the Nevada Test Site and in environmental risk assessment and management.

STEVE CARLE (center) received his B.S. and M.S. in engineering geoscience from the University of California at Berkeley in 1986 and 1987, respectively, and his Ph.D. in hydrologic science from the University of California at Davis in 1996. He came to Livermore as a postdoctoral fellow in 1997. In 2000, he joined the Geosciences and Environmental Technologies Division as a physicist. His research focuses on the development of geostatistical methods, the hydrogeologic modeling of groundwater flow and contaminant transport, and the integration of diverse data sets.

GORDON SEITZ (right) holds a B.S. in geology from San Diego State University (1983) and a Ph.D. in geological sciences from the University of Oregon at Eugene (1999). He joined the Laboratory as a postdoctoral fellow in 1999 to work at the Center for Accelerator Mass Spectrometry on the Bay Area Paleoseismic Experiment. His research interests include improving scientific understanding of past earthquake chronologies and interpreting patterns of fault behavior in space and time based on accelerator mass spectrometry carbon-14 dating, with special emphasis on the San Andreas Fault.